Validation of CO_2 Benefits of Installing ACCC® Conductors: Verification Assessment

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CTC Global Corporation

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Prepared by:
Dr. Gerard Mansell | Life Cycle Practitioner
gmansell@scsglobalservices.com

Reviewed by:
Keith Killpack | Technical Director

SCS global SERVICES
Setting the standard for sustainability™
2000 Powell Street, Ste. 600, Emeryville, CA 94608 USA
+1.510.452.8000 main | +1.510.452.8001 fax
www.SCSglobalServices.com

Executive Summary

CTC Global Corporation's (CTC) high-efficiency ACCC® Conductors reduce thermal sag, carry more current, and can reduce electrical transmission losses. As a result, ACCC® Conductors can reduce the need for electricity generation and thus, carbon dioxide (CO_2) emissions from power plants. To provide independent validation of this reduction in CO_2 emissions, CTC contracted SCS Global Services (SCS) to compare the line losses and CO_2 emissions associated with ACCC® Conductors and conventional Aluminum Conductor Steel-Reinforced (ACSR) conductors. This comparison was completed using ISO 14044:2006, an international standard governing environmental claims based in life cycle assessment.

To calculate line losses and related CO_2 emissions for each technology, SCS used the Conductor Comparison Program (CCP) developed by CTC. Using CCP, the performance of the ACSR and ACCC® Technologies were compared in five scenarios of similar design characteristics and identical operating conditions, ambient conditions, and grid power generation mix. Based on SCS' findings, the ACCC® technology in lieu of ACSR will reduce line losses and associated CO_2 emissions by 27-31% over at least the following range of evaluated parameters. Based on the breadth of design scenarios considered, SCS concludes that the ACCC® Conductor reduces CO_2 emissions associated with transmission line operation, when compared to ACSR technology installations of similar design specifications in identical operating settings. Although the actual CO_2 benefit will vary on a project-by-project basis, installation of ACCC® Technology in lieu of ACSR of the same specifications clearly provides a way to reduce CO_2 emissions from transmission line losses.

SCS also independently reviewed the methods used in the CCP, and found that the output of the CCP provides a valid estimate of the line losses and CO_2 benefits of using ACCC® Conductors compared to ACSR within a reasonable range of design scenarios. **Table 1**, below presents the scenario characteristics, as well as the evaluated reductions in CO_2 emissions and line losses for each, as calculated by SCS.

Table 1. Summary of the characteristics for the five scenarios.

				Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Design Scenario Characteristics	Line Length (mi)			20	30	40	50	60
	Conductor Size	ACCC®	Name	Casablanca	Fort Worth	Munich	Dublin	London
			Diameter (in)	0.807	1.240	1.293	1.108	1.315
		ACSR	Name	Ibis	Olive	Finch	Drake	Grackle
			Diameter (in)	0.783	1.240	1.120	1.108	1.338
	Voltage (kV) / Peak Operating Amps			110 / 650	150 / 1100	220 / 1200	345 / 2100	400 / 2700
	Annual Load Factor			50%	50%	50%	50%	50%
	# of Cond. Bundled / Cond. Per Phase/ Circuits			1 / 1 / 1	1 / 1 / 1	1 / 1 / 1	2 / 2 / 1	2 / 2 / 1
	Installation Location			India	Indonesia	Chile	USA	Germany
	Regional Grid Emission Factor (kg CO_2/kWh)			0.926	0.809	0.483	0.516	0.622
Results	Line Losses (MWh/yr)	ACCC Total		12,877	23,432	33,645	89,947	126,565
		ACSR Total		18,542	31,933	48,157	123,064	173,701
		ACCC Reduction		5,665 (31%)	8,501 (27%)	14,512 (30%)	33,117 (27%)	47,136 (27%)
	Emissions from Line Losses (metric tons CO_2/yr)	ACCC Total		11,921	18,961	16,253	46,430	78,785
		ACSR Total		17,166	25,840	23,264	63,524	108,099
		ACCC Reduction		5,245 (31%)	6,879 (27%)	7,011 (30%)	17,094 (27%)	29,314 (27%)

Introduction

CTC Global's high-temperature low-sag (HTLS) Aluminum Conductor Composite Core (ACCC®) conductors reduce thermal sag, carry more current, enable longer spans between support structures, and can reduce electrical transmission losses. Because of the reduction in line losses, the use of CTC Global's ACCC® Conductors instead of competing technologies will potentially reduce the need for electricity generation, which can lead to reduced carbon dioxide (CO_2) emissions. SCS was contracted by CTC Global to complete an assessment of the line losses and associated emissions reductions of the ACCC® Technology compared to conventional Aluminum Conductor Steel-Reinforced (ACSR) conductors using the ISO 14044:2006 standard, an international standard governing environmental claims based in life cycle assessment. The reductions in line losses achieved by the ACCC® Technology serve as the bases for emission reduction claims, as less energy generation (and thus fewer emissions) are required to produce the same energy output.

The ability of ACCC® Conductors to reduce CO_2 emissions in five installation scenarios were considered, under conditions of similar design characteristics and identical operating conditions, ambient conditions, and grid power generation mix. The design scenario characteristics are discussed in the following sections and summarized in Table 2.

It was determined that the use of the ACCC® Technology in lieu of the ACSR technology results in 27-31% reduction in both line losses and CO_2 emissions among the five scenarios (see Table 5). Based on this finding, SCS concludes that the ACCC® Conductor provides a way to reduce CO_2 emissions associated with transmission line operation, although when compared to ACSR technology installation, the specific CO_2 benefits will vary on a project-by-project basis. SCS also confirms that the Conductor Comparison Program (CCP) tool provides a reasonable way to estimate reductions in line losses and CO_2 emissions associated with the use of ACCC® Conductors in lieu of conventional ACSR conductors.

Background and Context

The verification assessment was conducted according to the ISO 14044:2006[1] standard, an internationally recognized standard for Life Cycle Assessment (LCA). LCA is a tool for evaluating the environmental performance of products from cradle-to-grave, including manufacturing, use, and disposal. Conducting this verification assessment using LCA conforming to this ISO standard gives users of the study confidence in the results and the claim.

The ISO 14044:2006 standard was created by the International Organization for Standardization, an independent, non-governmental international organization which develops voluntary international standards. The ISO 14044 standards specifies the requirements and guidelines required for carrying out an LCA study in order to produce a robust and defensible assessment. It is the standard used globally as the basis of LCA studies and claims.

[1] ISO 14044: Environmental management – Life cycle assessment requirements and guidelines.

Scope and Methodology Used in the Claim

As required by ISO 14044, the LCA-based verification assessment followed four phases: Goal and Scope Definition; Life Cycle Inventory; Life Cycle Impact Assessment; and Interpretation. These phases are described in further detail in the following sections.

Goal and Scope Definition

The scope of this assessment included a comparison of installation of an identical length of conductor line, using ACCC® and ACSR conductors. The ACSR technology was carefully selected as a comparison for the ACCC® Conductors, as it is a reasonable benchmark product with identical function and dominant market share. This ensures a meaningful and fair comparison between the two technologies. Five scenarios were considered, each with specific design characteristics which are reasonable installation scenarios for both products (see Table 2). The scope of allowable claims in this verification includes these scenarios.

The scope of the assessment is cradle-to-grave; however, the line losses arising during use of transmission lines is the dominant source of impacts. As the manufacturing, maintenance, and end-of-life stages will be minor in terms of impact and are similar between the two products, they were not quantified but assumed to be identical for the two technologies. For the purposes of this assessment, only climate change impacts were considered.

The timeframe of the assessment is 1 year of operation following installation.

Life Cycle Inventory

The increased generation of electricity required to compensate for line losses is the only resource input included, as only the use phase is considered in this assessment. CO_2 is the only emission considered. Emissions associated with producing the fuels used in grid electricity generation were not included, as there was insufficient data of comparable quality for these emissions across all of the regions considered in the scenarios; but as this would result in a larger benefit for the ACCC® Conductor(due to reduced need for fuel production as a result of reduced line losses), it is an acceptable conservative exclusion.

SCS calculated line losses (in MWh) and CO_2 reductions using the CCP tool. During the process, SCS reviewed the data and equations used in the CCP. Calculations in this tool were reviewed against the *IEEE 738 Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors* and other published equations. SCS validated the output of the tool and found it suitable for use in calculating the quantified CO_2 benefits of ACCC® Conductors. The line losses and CO_2 reductions were calculated using the CCP tool, according to the scenario characteristics defined in the next section. Based on this review, SCS has confidence in the CCP outputs for the five selected scenarios included in the verification assessment.

Life Cycle Impact Assessment

The impact category considered in the assessment is Global Warming. Global Warming Potential evaluated over 100 year time horizon (GWP-100) values were used as the basis of the calculations.

Interpretation

The LCA study found that use of ACCC® Conductors in lieu of ACSR conductors demonstrates reductions in line losses of 27-31%, which result in CO_2 emission reductions of 27-31%.

Design Scenarios Included in the Assessment

CTC identified five reasonable installation scenarios to compare CO_2 emissions associated with ACCC® Conductor and ACSR installations, and to serve as the basis of comparison. This included identification of a set of salient design characteristics (specified with numerical parameters) which represent a reasonable range of installation conditions. The following design scenario characteristics were used to define each of the five scenarios.

- Line Length
- Conductor Diameter
- Voltage
- Peak Operating Amps
- Annual Load Factor
- Number of Conductors Bundled
- Conductors per Phase
- Number of Circuits
- Region of Installation

These scenarios, and specific design scenario characteristics, are provided in Table 2 below.

Table 2. Design scenario characteristics for the five scenarios included in the verification assessment.

Scenario/Region	Line Length (mi)	Conductor Size				Voltage (kV)	Peak Operating Amps	Annual Load Factor	Conductors per Phase	Circuits
		ACCC®		ACSR						
		Name	Diameter (in)	Name	Diameter (in)					
1: India	20	Casablanca	0.807	Ibis	0.783	110	650	50%	1	1
2: Indonesia	30	Fort Worth	1.240	Olive	1.240	150	1100	50%	1	1
3: Chile	40	Munich	1.293	Finch	1.120	220	1200	50%	1	1
4: USA	50	Dublin	1.108	Drake	1.108	345	2100	50%	2	1
5: Germany	60	London	1.315	Grackle	1.338	400	2700	50%	2	1

Several design scenario characteristics were validated to confirm that the values for each scenario were reasonable. These include:

Annual Load Factor: 50% annual load factor was selected for all scenarios. This is a reasonable mid-range value for all scenarios. Typical demand load factors range from 10 to 60%[2], and load factors for transmissions lines are expected to be similar to this range or higher.

Conductor Size: Weight and diameter must be comparable between conductors in each scenario in order to make a robust comparison. SCS confirmed that conductor weight per unit length for the baseline conductor was comparable to the ACCC® Conductor in each scenario using product specification documents[3].

Peak Operating Amps: SCS confirmed that the selected values of peak operating amps were appropriate for the ACSR conductors in each scenario using product specifications[4]. This included validation that steady-temperature at peak ampacity was within the acceptable tolerances (maximum allowable temperature for each product)[5,6,7,8].

Choice of Baseline Technology: SCS confirmed that ACSR is an appropriate baseline technology through a literature review of multiple sources.[9] SCS compared the market penetration of ACSR using data from the Electric Power Research Institute provided by CTC. According to this data, installations of ACSR conductors represent over 500,000 miles in the USA alone, compared with less than 25,000 miles of ACCC® Conductors globally. Based on these data sources, SCS has concluded that there is no reason to doubt the dominance of ACSR in the global market, making it reasonable to use as a baseline technology for comparison with ACCC® Technology.

Ambient Conditions

The ambient conditions selected for the verification assessment are provided in Table 3 below. These values are a reasonable representation of transmission line operating conditions. The ambient conditions were held constant across all scenarios while other design scenario parameters were varied as the basis of comparison between the five scenarios. These conditions do not necessarily represent the anticipated ambient conditions for each scenario; but rather were held constant to demonstrate the change in line losses and CO_2 emissions resulting from use of the ACCC® Conductor in lieu of ACSR conductors. In evaluating the changes in line losses and CO_2 emissions associated with actual projects, more specific ambient conditions should be used.

[2] http://www.coned.com/customercentral/demandbilling.asp
[3] Southwire Product Catalog – Aluminum Conductor. Steel Reinforced. Bare. http://www.southwire.com/ProductCatalog/XTEInterfaceServlet?contentKey=prodcatsheet16
[4] Ibid.
[5] http://www.southwire.com/support/RevisingACSRCapacityAssumptions.htm
[6] http://www.atc10yearplan.com/2011/documents/CR-0061.pdf
[7] https://www.pjm.com/~/media/planning/design-engineering/maac-standards/bare-overhead-transmission-conductor-ratings.ashx
[8] http://www.aluminum.org/sites/default/files/Chapter%206%20Operating%20Performance%20and%20Problems.pdf
[9] http://pdc-cables.com/oh_norman_transconduct.pdf

Table 3. Ambient conditions used in the verification assessment for all five design scenarios.

Parameter	Selected Value	Parameter	Selected Value	Parameter	Selected Value
Sun Radiation	89.9 W/ft^2	Solar absorptivity	0.6	Month	June
Ambient temperature	30°C	Emissivity	0.6	Day of month	9
Wind speed	2 ft/sec	Wind angle	90°	Time	15:00
Elevation	150 ft	Azimuth of line	0	Atmosphere	Clear
		Latitude	34		

Validation of CCP Tool

SCS reviewed the inputs and equations to the CTC Conductor Comparison Program (CCP) in order to validate the output of the tool for the five scenarios included in the assessment. SCS validated the calculations of the CCP tool by recalculating several outputs in accordance with the ISO 14044 standard, with detailed equations and data taken from the *IEEE 738 Standard for Calculating the Current-Temperature Relationship of Bare Overhead Conductors*. The detailed validation process is discussed in Appendix B. Based on the assessment of the CCP tool inputs and equations, SCS is confident in the outputs of the tool for the five verification scenarios and its use to calculate results.

Calculating Results

SCS input the design scenario characteristics for each scenario (presented in Table 4) into the CCP tool to evaluate the line losses and CO_2 emissions for the same design installation using the ACCC® Conductors and ACSR. Output reports from the CPP tool for each scenario are provided in Appendix A.

Table 4. Design scenario characteristics used in the CCP tool.

		Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
Line Length (mi)		20	30	40	50	60
ACCC®	**Name**	Casablanca	Fort Worth	Munich	Dublin	London
	Diameter (in)	0.807	1.240	1.293	1.108	1.315
ACSR	**Name**	Ibis	Olive	Finch	Drake	Grackle
	Diameter (in)	0.783	1.240	1.120	1.108	1.338
Voltage (kV) / Peak Operating Amps		110 / 650	150 / 1100	220 / 1200	345 / 2100	400 / 2700
Annual Load Factor		50%	50%	50%	50%	50%
# of Cond. Bundled / Cond. Per Phase / Circuits		1 / 1 / 1	1 / 1 / 1	1 / 1 / 1	2 / 2 / 1	2 / 2 / 1
Region		India	Indonesia	Chile	USA	Germany
Emission Factor (kg/kWh)		0.926	0.809	0.483	0.516	0.622

Verification Assessment Findings

The results of the verification assessment can be found in Table 5 below. As illustrated in the table, ACCC® Conductors demonstrate significant reductions in line losses, and associated emissions reductions, in all scenarios. The percent reduction in line losses of the ACCC® Conductors over ACSR ranged from 27% to 31%. Absolute reductions in line losses and associated emissions reductions are presented in the table below.

Table 5. Results of verification assessment calculations. Line losses are given in MWh per year and emissions reductions are given in metric tons (MT) per year.

	Line Losses (MWh/year)			CO_2 Emissions related to Line Losses (metric tons per year)		
Scenario	**ACCC**	**ACSR**	**ACCC Reduction**	**ACCC**	**ACSR**	**ACCC Reduction**
Scenario 1	12,877	18,542	**5,665 (31%)**	11,921	17,166	**5,245 (31%)**
Scenario 2	23,432	31,933	**8,501 (27%)**	18,961	25,840	**6,879 (27%)**
Scenario 3	33,645	48,157	**14,512 (30%)**	16,253	23,264	**7,011 (30%)**
Scenario 4	89,947	123,064	**33,117 (27%)**	46,430	63,524	**17,094 (27%)**
Scenario 5	126,565	173,701	**47,136 (27%)**	78,785	108,099	**29,314 (27%)**

SCS reviewed CTC's Conductor Comparison Program (CCP) for its validity in calculating line losses and the resulting CO_2 emissions for ACCC® and ACSR transmission line technologies. Based on this review, and assuming installations where ACCC® Technology substitutes for ACSR lines of similar design characteristics and identical operating conditions, ambient conditions, and grid power generation mix, SCS is able to substantiate the following claims:

- SCS verifies that use of the ACCC® Technology in lieu of ACSR will reduce line losses and associated CO_2 emissions by 27-31% over at least the following range of evaluated parameters:
  - Line length: 20 to 60 miles
  - Diameter: 0.7 to 1.3 inches
  - Voltage: 110 to 400 kV
  - Peak operating amps: 650 to 2700 amps
- SCS verifies use of the CCP tool as a reasonable way to estimate reductions in line losses and associated CO_2 emissions achieved by installing ACCC® Conductors in lieu of ACSR technologies.
- SCS confirms, and has no reason to doubt, that use of the ACCC® Technology in lieu of ACSR will reduce line losses and associated CO_2 emissions in general applications.

Significance of Findings

SCS found that installation of ACCC® Conductors reduce line losses by 27 to 31 percent over conventional ACSR conductors for the range of scenarios described in the report. SCS validated that, under these design conditions, use of the ACCC® Technology over the ACSR conductor results in concomitant CO_2 emissions reductions of between 27 and 31 percent. Based on the breadth of different installations considered in these scenarios, including a four-fold range of operating voltages and amperages with emission factors from five different countries, SCS concludes that the ACCC® Conductor provides a way to reduce CO_2 emissions associated with transmission line operation, when compared to ACSR technology installations of identical diameter, line length, voltage, annual load factor, number of conductors bundled, conductors per phase, number of circuits, and peak operating amperage. In actual installations, specific line loss reductions and CO_2 reduction benefits will vary on a project-by-project basis, and must be verified after installation is completed. SCS verifies that use of the ACCC® Technology in lieu of ACSR will reduce line losses and associated CO_2 emissions by 27-31% over at least the following range of evaluated parameters

As part of the verification assessment, SCS also validated the output of the CCP tool, and found that the output of the CCP tool provides a valid estimate of the line loss reduction and CO_2 benefits of ACCC® Conductors compared to ACSR within a reasonable range of applicable design scenario characteristics (e.g., peak operating amps, etc.), and provided that the correct regional grid CO_2 emissions factor is used. SCS verifies that the CCP tool provides a reasonable way to estimate reduction in line losses and greenhouse gas emissions associated with the use of ACCC® Conductors in lieu of conventional ACSR conductors.

Appendix A: Summary CPP Tool Inputs and Outputs Used As Basis of Claim

The output summaries from the CCP tool used to obtain verification results for each design scenario are provided in this Appendix. Design scenario characteristics used for the verification assessment are provided in Table 2 of the report.

Scenario	Region
1.	India
2.	Indonesia
3.	Chile
4.	USA
5.	Germany

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Main Comparison Report

Project Name: SCS - India
Project Location: India

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	398 kcmil IBIS	540 kcmil CASABLANCA		
Aluminum Area (kcmil)	397.5	540.0		
Diameter (in.)	0.783	0.807		
Rated Strength (lbf)	16,300.0	22,726.3		
Weight (lb/kft)	546.6	560.5		
Electrical Characteristics				
DC Resistance at 20°C (ohms/kft)	0.0428	0.0312		
AC Resistance at 25°C (ohms/kft)	0.0438	0.0320		
AC Resistance at 75°C (ohms/kft)	0.0523	0.0382		
Conductors per phase	1	1		
Number of Circuits	1	1		
Ampacity (A) at Temperature (°C)	(60) - 432	(60) - 509		
Ampacity (A) at Temperature 2 (°C)	(125) - 812	(125) - 959		
Ampacity (A) at Temperature 3 (°C)	(100) - 700	(100) - 826		
Ampacity (A) at Rated Operating Temp (°C)	(75) - 554	(180) - 1,181		
Ampacity (A) at Maximum Temp (°C)	(100) - 700	(200) - 1,249		
Solar Absorptivity	0.60	0.60		
Emissivity	0.60	0.60		
Economic Analysis				
Line Losses (20.00 miles, 650 Peak Amps)				
Steady-State Temperature (ºC) at Peak Ampacity	90	75		
Resistance at Peak Operating Amps (ohm/mile)	0.29043	0.20170		
First Year Line Losses (MWh)	18,542	12,877		
Difference in First Year Line Losses vs Base Conductor(MWh)	--	-5,665		
% Difference in First Year Line Losses vs Base Conductor (%)	--	-31 (%)		
First Year Line Loss Savings vs. Base Conductor Base Conductor (USD/Year)	--	283,243		
Line Loss Savings per foot of Conductor vs. Base Conductor (USD/ft/Year)	--	0.89		
30 year Line Loss Savings vs Base Conductor (USD)	--	8,497,276		
Difference in First Year CO_2 Generated vs Base Conductor (MT)	--	-5,244		
Difference in 30 year CO_2 Generated vs Base Conductor (MT)	--	-157,334		
First Year Value of CO_2	--	131,100		
First Year Equivalent Number of Cars	--	1,008		
First Year Equivalent Number of Homes	--	467		
Generation Savings				
Generation Capacity Required to Supply Line Losses (MW)	2.12	1.47		
Difference in Generation Capacity vs Base Conductor (MW)	--	-0.65		
Difference in Capital Cost of Capacity vs Base Conductor (USD)	--	-647,000		
Initial Sag/Tension at Above-Stringing Temperature (15 °C)				
Ruling Span (ft)	500.0	500.0		
% RTS	20.0	20.0		
Sag at Initial Sagging Temperature (ft)	5.24	3.86		
Total Initial Tension at Structure at Sagging Temperature (lbf)	3,260.5	4,546.0		
Total Conductor Weight/phase (lb/kft)	546.6	560.5		

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Main Comparison Report

Project Name: SCS - India
Project Location: India

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	398 kcmil IBIS	540 kcmil CASABLANCA		
Sag/Tension at Stringing Temperature				
Sag at Peak Operating Amps				
Temp (ºC)	90	75		
Sag (ft)	10.73	6.04		
Total Structure Tension (lbf)	1,598.3	2,905.4		
Sag at Rated Operating Temperature				
Temp (ºC)	75	180		
Sag (ft)	9.85	6.32		
Total Structure Tension (lbf)	1,740.9	2,774.4		
Sag at Maximum Temperature				
Temp (ºC)	100	200		
Sag (ft)	11.07	6.38		
Total Structure Tension (lbf)	1,549.5	2,749.8		
Max Allowable Temperature at Sag of 16 ft.				
Max. Allowable Temp (ºC)	100	200		
Sag (ft)	11.07	6.38		
Total Structure Tension (lbf)	1,549.5	2,749.8		
Ampacity (A)	700	1,249		
Wind/Ice or Cold Temperature Sag/Tension				
NESC HEAVY				
Total Sag (ft)	8.68	9.21		
Total Structure Tension (lbf)	6,385.1	6,122.4		
% RTS	39.2	26.9		
Max. Allowable Tension (lbf):	14,000.00	14,000.00		
Max. Tension (% RTS)	60.00	60.00		
Knee Point Temperature Sag/Tension				
Knee Point Temperature (°C)	85	47		
Sag (ft)	10.56	5.99		
Total Structure Tension (lbf)	1,623.7	2,930.0		

Assumptions and Inputs:
Line and Load: Line Length (miles) = 20.00, Voltage (kV) = 110, Voltage Type = AC, Phases/Circuit = 3, Peak Amps = 650, Total Peak Power (MVA) = 124,Load Factor (%) = 50.
Environmental Inputs: Sun Radiation (W/ft²) = 96.3, Ambient Temp. (ºC) = 30.0, Elevation (ft) = 150, Wind Angle (deg.) = 90, Latitude (neg = South) = 34, Wind (ft/sec) = 2.00.
Wind/Ice or Cold Temperature Sag/Tension: Temperature (°C) = , Windspeed(Loading) (mph) = 39.5, K-Factor (lb/ft) = 0.30, Radial Ice Thickness (in.) = , Ice Density (lb/ft³) = 57.
Economic: Cost of Energy Generation (USD/MWh) = 50.00, Installed Generation Cost (USD/kW) = 1000.00, CO_2 (lb/kWh) = 2.041.

Note 1:Conductor Ampacity and Temperature calculations based on **IEEE 738-2006**.

Note 2:Red Text: Maximum Conductor Temperature Exceeded

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Main Comparison Report

Project Name: SCS - Indonesia
Project Location: Indonesia

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1025 kcmil OLIVE	1300 kcmil FORT WORTH		
Aluminum Area (kcmil)	1,025.0	1,300.4		
Diameter (in.)	1.240	1.240		
Rated Strength (lbf)	35,744.0	42,900.0		
Weight (lb/kft)	1,317.0	1,312.0		
Electrical Characteristics				
DC Resistance at 20°C (ohms/kft)	0.0168	0.0130		
AC Resistance at 25°C (ohms/kft)	0.0187	0.0137		
AC Resistance at 75°C (ohms/kft)	0.0215	0.0162		
Conductors per phase	1	1		
Number of Circuits	1	1		
Ampacity (A) at Temperature (°C)	(60) - 741	(60) - 856		
Ampacity (A) at Temperature 2 (°C)	(75) - 974	(75) - 1,120		
Ampacity (A) at Temperature 3 (°C)	(100) - 1,258	(100) - 1,436		
Ampacity (A) at Rated Operating Temp (°C)	(75) - 974	(180) - 2,089		
Ampacity (A) at Maximum Temp (°C)	(100) - 1,258	(200) - 2,216		
Solar Absorptivity	0.60	0.60		
Emissivity	0.60	0.60		
Economic Analysis				
Line Losses (30.00 miles, 1100 Peak Amps)				
Steady-State Temperature (ºC) at Peak Ampacity	85	74		
Resistance at Peak Operating Amps (ohm/mile)	0.11643	0.08543		
First Year Line Losses (MWh)	31,933	23,432		
Difference in First Year Line Losses vs Base Conductor(MWh)	--	-8,501		
% Difference in First Year Line Losses vs Base Conductor (%)	--	-27 (%)		
First Year Line Loss Savings vs. Base Conductor Base Conductor (USD/Year)	--	425,060		
Line Loss Savings per foot of Conductor vs. Base Conductor (USD/ft/Year)	--	0.89		
30 year Line Loss Savings vs Base Conductor (USD)	--	12,751,814		
Difference in First Year CO_2 Generated vs Base Conductor (MT)	--	-6,879		
Difference in 30 year CO_2 Generated vs Base Conductor (MT)	--	-206,380		
First Year Value of CO_2	--	171,975		
First Year Equivalent Number of Cars	--	1,323		
First Year Equivalent Number of Homes	--	612		
Generation Savings				
Generation Capacity Required to Supply Line Losses (MW)	3.65	2.67		
Difference in Generation Capacity vs Base Conductor (MW)	--	-0.97		
Difference in Capital Cost of Capacity vs Base Conductor (USD)	--	-970,000		
Initial Sag/Tension at Above-Stringing Temperature (15 °C)				
Ruling Span (ft)	500.0	500.0		
% RTS	20.0	20.0		
Sag at Initial Sagging Temperature (ft)	5.76	4.78		
Total Initial Tension at Structure at Sagging Temperature (lbf)	7,149.2	8,580.1		
Total Conductor Weight/phase (lb/kft)	1,317.0	1,312.0		

CTC GLOBAL

Main Comparison Report

2/26/2020 4:02:24 PM GMT (or UTC)

Project Name: SCS - Indonesia
Project Location: Indonesia

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1025 kcmil OLIVE	1300 kcmil FORT WORTH		
Sag/Tension at Stringing Temperature				
Sag at Peak Operating Amps				
Temp (ºC)	85	74		
Sag (ft)	11.57	7.99		
Total Structure Tension (lbf)	3,576.0	5,145.5		
Sag at Rated Operating Temperature				
Temp (ºC)	75	180		
Sag (ft)	10.82	8.32		
Total Structure Tension (lbf)	3,820.0	4,943.5		
Sag at Maximum Temperature				
Temp (ºC)	100	200		
Sag (ft)	12.62	8.38		
Total Structure Tension (lbf)	3,279.8	4,906.2		
Max Allowable Temperature at Sag of 15 ft.				
Max. Allowable Temp (ºC)	100	200		
Sag (ft)	12.62	8.38		
Total Structure Tension (lbf)	3,279.8	4,906.2		
Ampacity (A)	1,258	2,216		
Wind/Ice or Cold Temperature Sag/Tension				
NESC HEAVY				
Total Sag (ft)	7.21	7.85		
Total Structure Tension (lbf)	12,217.9	11,195.6		
% RTS	34.2	26.1		
Max. Allowable Tension (lbf):	14,000.00	14,000.00		
Max. Tension (% RTS)	60.00	60.00		
Knee Point Temperature Sag/Tension				
Knee Point Temperature (°C)	112	56		
Sag (ft)	13.42	7.94		
Total Structure Tension (lbf)	3,086.3	5,177.7		

Assumptions and Inputs:
Line and Load: Line Length (miles) = 30.00, Voltage (kV) = 150, Voltage Type = AC, Phases/Circuit = 3, Peak Amps = 1100, Total Peak Power (MVA) = 286,Load Factor (%) = 50.
Environmental Inputs: Sun Radiation (W/ft²) = 96.3, Ambient Temp. (ºC) = 30.0, Elevation (ft) = 150, Wind Angle (deg.) = 90, Latitude (neg = South) = 34, Wind (ft/sec) = 2.00.
Wind/Ice or Cold Temperature Sag/Tension: Temperature (°C) = , Windspeed(Loading) (mph) = 39.5, K-Factor (lb/ft) = 0.30, Radial Ice Thickness (in.) = , Ice Density (lb/ft³) = 57.
Economic: Cost of Energy Generation (USD/MWh) = 50.00, Installed Generation Cost (USD/kW) = 1000.00, CO_2 (lb/kWh) = 1.784.

Note 1:Conductor Ampacity and Temperature calculations based on **IEEE 738-2006**.

Note 2:Red Text: Maximum Conductor Temperature Exceeded

CTC GLOBAL

Main Comparison Report

2/26/2020 4:05:40 PM GMT (or UTC)

Project Name: SCS - Chile
Project Location: Chile

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1113 kcmil FINCH	1447 kcmil MUNICH		
Aluminum Area (kcmil)	1,113.0	1,447.0		
Diameter (in.)	1.120	1.293		
Rated Strength (lbf)	39,100.0	43,848.3		
Weight (lb/kft)	1,431.0	1,458.4		
Electrical Characteristics				
DC Resistance at 20°C (ohms/kft)	0.0154	0.0117		
AC Resistance at 25°C (ohms/kft)	0.0161	0.0124		
AC Resistance at 75°C (ohms/kft)	0.0197	0.0146		
Conductors per phase	1	1		
Number of Circuits	1	1		
Ampacity (A) at Temperature (°C)	(60) - 773	(60) - 921		
Ampacity (A) at Temperature 2 (°C)	(75) - 998	(75) - 1,201		
Ampacity (A) at Temperature 3 (°C)	(100) - 1,266	(100) - 1,538		
Ampacity (A) at Rated Operating Temp (°C)	(75) - 998	(180) - 2,239		
Ampacity (A) at Maximum Temp (°C)	(100) - 1,266	(200) - 2,376		
Solar Absorptivity	0.60	0.60		
Emissivity	0.60	0.60		
Economic Analysis				
Line Losses (40.00 miles, 1200 Peak Amps)				
Steady-State Temperature (ºC) at Peak Ampacity	93	75		
Resistance at Peak Operating Amps (ohm/mile)	0.11066	0.07731		
First Year Line Losses (MWh)	48,157	33,645		
Difference in First Year Line Losses vs Base Conductor(MWh)	--	-14,512		
% Difference in First Year Line Losses vs Base Conductor (%)	--	-30 (%)		
First Year Line Loss Savings vs. Base Conductor Base Conductor (USD/Year)	--	725,610		
Line Loss Savings per foot of Conductor vs. Base Conductor (USD/ft/Year)	--	1.15		
30 year Line Loss Savings vs Base Conductor (USD)	--	21,768,286		
Difference in First Year CO_2 Generated vs Base Conductor (MT)	--	-7,011		
Difference in 30 year CO_2 Generated vs Base Conductor (MT)	--	-210,317		
First Year Value of CO_2	--	175,275		
First Year Equivalent Number of Cars	--	1,348		
First Year Equivalent Number of Homes	--	624		
Generation Savings				
Generation Capacity Required to Supply Line Losses (MW)	5.50	3.84		
Difference in Generation Capacity vs Base Conductor (MW)	--	-1.66		
Difference in Capital Cost of Capacity vs Base Conductor (USD)	--	-1,657,000		
Initial Sag/Tension at Above-Stringing Temperature (15 °C)				
Ruling Span (ft)	500.0	500.0		
% RTS	20.0	20.0		
Sag at Initial Sagging Temperature (ft)	5.73	5.20		
Total Initial Tension at Structure at Sagging Temperature (lbf)	7,820.4	8,770.1		
Total Conductor Weight/phase (lb/kft)	1,431.0	1,458.4		

CTC GLOBAL

Main Comparison Report

2/26/2020 4:05:40 PM GMT (or UTC)

Project Name: SCS - Chile
Project Location: Chile

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1113 kcmil FINCH	1447 kcmil MUNICH		
Sag/Tension at Stringing Temperature				
Sag at Peak Operating Amps				
Temp (ºC)	93	75		
Sag (ft)	11.77	8.72		
Total Structure Tension (lbf)	3,820.2	5,242.8		
Sag at Rated Operating Temperature				
Temp (ºC)	75	180		
Sag (ft)	10.48	9.05		
Total Structure Tension (lbf)	4,286.2	5,050.9		
Sag at Maximum Temperature				
Temp (ºC)	100	200		
Sag (ft)	12.16	9.11		
Total Structure Tension (lbf)	3,698.6	5,015.4		
Max Allowable Temperature at Sag of 15 ft.				
Max. Allowable Temp (ºC)	100	200		
Sag (ft)	12.16	9.11		
Total Structure Tension (lbf)	3,698.6	5,015.4		
Ampacity (A)	1,266	2,376		
Wind/Ice or Cold Temperature Sag/Tension				
NESC HEAVY				
Total Sag (ft)	6.78	8.13		
Total Structure Tension (lbf)	13,113.5	11,495.7		
% RTS	33.5	26.2		
Max. Allowable Tension (lbf):	14,000.00	14,000.00		
Max. Tension (% RTS)	60.00	60.00		
Knee Point Temperature Sag/Tension				
Knee Point Temperature (°C)	98	57		
Sag (ft)	12.11	8.68		
Total Structure Tension (lbf)	3,713.8	5,262.6		

Assumptions and Inputs:
Line and Load: Line Length (miles) = 40.00, Voltage (kV) = 220, Voltage Type = AC, Phases/Circuit = 3, Peak Amps = 1200, Total Peak Power (MVA) = 457,Load Factor (%) = 50.
Environmental Inputs: Sun Radiation (W/ft²) = 89.9, Ambient Temp. (ºC) = 30.0, Elevation (ft) = 150, Wind Angle (deg.) = 90, Latitude (neg = South) = -36, Wind (ft/sec) = 2.00.
Wind/Ice or Cold Temperature Sag/Tension: Temperature (°C) = , Windspeed(Loading) (mph) = 39.5, K-Factor (lb/ft) = 0.30, Radial Ice Thickness (in.) = , Ice Density (lb/ft³) = 57.
Economic: Cost of Energy Generation (USD/MWh) = 50.00, Installed Generation Cost (USD/kW) = 1000.00, CO_2 (lb/kWh) = 1.065.

Note 1:Conductor Ampacity and Temperature calculations based on **IEEE 738-2006**.

Note 2:Red Text: Maximum Conductor Temperature Exceeded

CTC GLOBAL

2/26/2020 4:01:13 PM GMT (or UTC)

Main Comparison Report

Project Name: SCS - USA
Project Location: USA

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	795 kcmil DRAKE	1035 kcmil DUBLIN		
Aluminum Area (kcmil)	795.0	1,035.1		
Diameter (in.)	1.108	1.108		
Rated Strength (lbf)	31,500.0	41,208.9		
Weight (lb/kft)	1,094.0	1,064.0		
Electrical Characteristics				
DC Resistance at 20°C (ohms/kft)	0.0214	0.0163		
AC Resistance at 24°C (ohms/kft)	0.0221	0.0169		
AC Resistance at 75°C (ohms/kft)	0.0263	0.0201		
Conductors per phase	2	2		
Number of Circuits	1	1		
Ampacity (A) at Temperature (°C)	(60) - 1,329	(60) - 1,521		
Ampacity (A) at Temperature 2 (°C)	(75) - 1,720	(75) - 1,968		
Ampacity (A) at Temperature 3 (°C)	(100) - 2,191	(100) - 2,508		
Ampacity (A) at Rated Operating Temp (°C)	(75) - 1,720	(180) - 3,621		
Ampacity (A) at Maximum Temp (°C)	(100) - 2,191	(200) - 3,837		
Solar Absorptivity	0.60	0.60		
Emissivity	0.60	0.60		
Economic Analysis				
Line Losses (50.00 miles, 2100 Peak Amps)				
Steady-State Temperature (ºC) at Peak Ampacity	95	80		
Resistance at Peak Operating Amps (ohm/mile)	0.14774	0.10798		
First Year Line Losses (MWh)	123,064	89,947		
Difference in First Year Line Losses vs Base Conductor(MWh)	--	-33,117		
% Difference in First Year Line Losses vs Base Conductor (%)	--	-27 (%)		
First Year Line Loss Savings vs. Base Conductor Base Conductor (USD/Year)	--	1,655,831		
Line Loss Savings per foot of Conductor vs. Base Conductor (USD/ft/Year)	--	1.05		
30 year Line Loss Savings vs Base Conductor (USD)	--	49,674,922		
Difference in First Year CO_2 Generated vs Base Conductor (MT)	--	-17,095		
Difference in 30 year CO_2 Generated vs Base Conductor (MT)	--	-512,837		
First Year Value of CO_2	--	410,280		
First Year Equivalent Number of Cars	--	3,288		
First Year Equivalent Number of Homes	--	1,522		
Generation Savings				
Generation Capacity Required to Supply Line Losses (MW)	14.05	10.27		
Difference in Generation Capacity vs Base Conductor (MW)	--	-3.78		
Difference in Capital Cost of Capacity vs Base Conductor (USD)	--	-3,780,000		
Initial Sag/Tension at Above-Stringing Temperature (15 °C)				
Ruling Span (ft)	500.0	500.0		
% RTS	20.0	20.0		
Sag at Initial Sagging Temperature (ft)	5.43	4.04		
Total Initial Tension at Structure at Sagging Temperature (lbf)	12,601.7	16,484.2		
Total Conductor Weight/phase (lb/kft)	2,188.0	2,128.0		

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Main Comparison Report

2/26/2020 4:01:13 PM GMT (or UTC)

Project Name: SCS - USA
Project Location: USA

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	795 kcmil DRAKE	1035 kcmil DUBLIN		
Sag/Tension at Stringing Temperature				
Sag at Peak Operating Amps				
Temp (ºC)	95	80		
Sag (ft)	10.63	6.42		
Total Structure Tension (lbf)	6,462.1	10,372.0		
Sag at Rated Operating Temperature				
Temp (ºC)	75	180		
Sag (ft)	9.95	6.71		
Total Structure Tension (lbf)	6,899.9	9,934.1		
Sag at Maximum Temperature				
Temp (ºC)	100	200		
Sag (ft)	10.80	6.76		
Total Structure Tension (lbf)	6,360.2	9,849.9		
Max Allowable Temperature at Sag of 15 ft.				
Max. Allowable Temp (ºC)	100	200		
Sag (ft)	10.80	6.76		
Total Structure Tension (lbf)	6,360.2	9,849.9		
Ampacity (A)	2,191	3,837		
Wind/Ice or Cold Temperature Sag/Tension				
NESC HEAVY				
Total Sag (ft)	7.25	7.48		
Total Structure Tension (lbf)	21,666.5	20,752.9		
% RTS	34.4	25.2		
Max. Allowable Tension (lbf):	22,000.00	22,000.00		
Max. Tension (% RTS)	60.00	60.00		
Knee Point Temperature Sag/Tension				
Knee Point Temperature (°C)	76	48		
Sag (ft)	9.98	6.35		
Total Structure Tension (lbf)	6,877.3	10,488.3		

Assumptions and Inputs:
<u>Line and Load:</u> Line Length (miles) = 50.00, Voltage (kV) = 345, Voltage Type = AC, Phases/Circuit = 3, Peak Amps = 2100, Total Peak Power (MVA) = 1255,Load Factor (%) = 50.
<u>Environmental Inputs:</u> Sun Radiation (W/ft²) = 89.9, Ambient Temp. (ºC) = 30.0, Elevation (ft) = 150, Wind Angle (deg.) = 90, Latitude (neg = South) = 34, Wind (ft/sec) = 2.00.
<u>Wind/Ice or Cold Temperature Sag/Tension:</u> Temperature (°C) = , Windspeed(Loading) (mph) = 39.5, K-Factor (lb/ft) = 0.30, Radial Ice Thickness (in.) = , Ice Density (lb/ft³) = 57.
<u>Economic:</u> Cost of Energy Generation (USD/MWh) = 50.00, Installed Generation Cost (USD/kW) = 1000.00, CO_2 (lb/kWh) = 1.138.

Note 1:Conductor Ampacity and Temperature calculations based on **IEEE 738-2006**.

Note 2:Red Text: Maximum Conductor Temperature Exceeded

CTC GLOBAL

Main Comparison Report

2/26/2020 4:03:34 PM GMT (or UTC)

Project Name: SCS - Germany
Project Location: Germany

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1192 kcmil GRACKLE	1498 kcmil LONDON		
Aluminum Area (kcmil)	1,192.5	1,497.9		
Diameter (in.)	1.338	1.315		
Rated Strength (lbf)	41,900.0	46,040.5		
Weight (lb/kft)	1,531.4	1,510.8		
Electrical Characteristics				
DC Resistance at 20°C (ohms/kft)	0.0144	0.0113		
AC Resistance at 25°C (ohms/kft)	0.0151	0.0119		
AC Resistance at 75°C (ohms/kft)	0.0184	0.0141		
Conductors per phase	2	2		
Number of Circuits	1	1		
Ampacity (A) at Temperature (°C)	(60) - 1,640	(60) - 1,858		
Ampacity (A) at Temperature 2 (°C)	(75) - 2,146	(75) - 2,438		
Ampacity (A) at Temperature 3 (°C)	(100) - 2,746	(100) - 3,135		
Ampacity (A) at Rated Operating Temp (°C)	(75) - 2,146	(180) - 4,579		
Ampacity (A) at Maximum Temp (°C)	(100) - 2,746	(200) - 4,861		
Solar Absorptivity	0.60	0.60		
Emissivity	0.60	0.60		
Economic Analysis				
Line Losses (60.00 miles, 2700 Peak Amps)				
Steady-State Temperature (ºC) at Peak Ampacity	98	83		
Resistance at Peak Operating Amps (ohm/mile)	0.10512	0.07660		
First Year Line Losses (MWh)	173,701	126,565		
Difference in First Year Line Losses vs Base Conductor(MWh)	--	-47,136		
% Difference in First Year Line Losses vs Base Conductor (%)	--	-27 (%)		
First Year Line Loss Savings vs. Base Conductor Base Conductor (USD/Year)	--	2,356,812		
Line Loss Savings per foot of Conductor vs. Base Conductor (USD/ft/Year)	--	1.24		
30 year Line Loss Savings vs Base Conductor (USD)	--	70,704,361		
Difference in First Year CO_2 Generated vs Base Conductor (MT)	--	-29,335		
Difference in 30 year CO_2 Generated vs Base Conductor (MT)	--	-880,036		
First Year Value of CO_2	--	733,375		
First Year Equivalent Number of Cars	--	5,641		
First Year Equivalent Number of Homes	--	2,612		
Generation Savings				
Generation Capacity Required to Supply Line Losses (MW)	19.83	14.45		
Difference in Generation Capacity vs Base Conductor (MW)	--	-5.38		
Difference in Capital Cost of Capacity vs Base Conductor (USD)	--	-5,381,000		
Initial Sag/Tension at Above-Stringing Temperature (15 °C)				
Ruling Span (ft)	500.0	500.0		
% RTS	20.0	20.0		
Sag at Initial Sagging Temperature (ft)	5.72	5.13		
Total Initial Tension at Structure at Sagging Temperature (lbf)	16,760.7	18,416.7		
Total Conductor Weight/phase (lb/kft)	3,062.8	3,021.6		

CTC GLOBAL

Main Comparison Report

2/26/2020 4:03:34 PM GMT (or UTC)

Project Name: SCS - Germany
Project Location: Germany

Conductor Information	Base Conductor	Comparison Conductor #1	Not Selected	Not Selected
Type	ACSR	ACCC®		
Size (Unit - Code Word)	1192 kcmil GRACKLE	1498 kcmil LONDON		
Sag/Tension at Stringing Temperature				
Sag at Peak Operating Amps				
Temp (ºC)	98	83		
Sag (ft)	12.09	8.61		
Total Structure Tension (lbf)	7,961.9	11,000.9		
Sag at Rated Operating Temperature				
Temp (ºC)	75	180		
Sag (ft)	10.47	8.91		
Total Structure Tension (lbf)	9,178.6	10,625.4		
Sag at Maximum Temperature				
Temp (ºC)	100	200		
Sag (ft)	12.15	8.98		
Total Structure Tension (lbf)	7,919.2	10,550.9		
Max Allowable Temperature at Sag of 15 ft.				
Max. Allowable Temp (ºC)	100	200		
Sag (ft)	12.15	8.98		
Total Structure Tension (lbf)	7,919.2	10,550.9		
Ampacity (A)	2,746	4,861		
Wind/Ice or Cold Temperature Sag/Tension				
NESC HEAVY				
Total Sag (ft)	6.84	7.98		
Total Structure Tension (lbf)	28,233.7	23,952.5		
% RTS	33.7	26.0		
Max. Allowable Tension (lbf):	30,000.00	30,000.00		
Max. Tension (% RTS)	60.00	60.00		
Knee Point Temperature Sag/Tension				
Knee Point Temperature (°C)	98	57		
Sag (ft)	12.10	8.56		
Total Structure Tension (lbf)	7,951.8	11,058.9		

Assumptions and Inputs:
Line and Load: Line Length (miles) = 60.00, Voltage (kV) = 400, Voltage Type = AC, Phases/Circuit = 3, Peak Amps = 2700, Total Peak Power (MVA) = 1871,Load Factor (%) = 50.
Environmental Inputs: Sun Radiation (W/ft²) = 96.3, Ambient Temp. (ºC) = 30.0, Elevation (ft) = 150, Wind Angle (deg.) = 90, Latitude (neg = South) = 34, Wind (ft/sec) = 2.00.
Wind/Ice or Cold Temperature Sag/Tension: Temperature (°C) = , Windspeed(Loading) (mph) = 39.5, K-Factor (lb/ft) = 0.30, Radial Ice Thickness (in.) = , Ice Density (lb/ft³) = 57.
Economic: Cost of Energy Generation (USD/MWh) = 50.00, Installed Generation Cost (USD/kW) = 1000.00, CO_2 (lb/kWh) = 1.372.

Note 1:Conductor Ampacity and Temperature calculations based on **IEEE 738-2006**.

Note 2:Red Text: Maximum Conductor Temperature Exceeded

Appendix B: Validation of CCP Tool Equations and Calculations

Using the IEEE standard, conductor current, I, was calculated according to Equation 1, for each scenario. Upon completion of this assessment, it was confirmed that the outputs of the tool were materially correct. The relevant design scenario characteristics for each scenario were then input into the tool to obtain verified results for each scenario.

$$I = \sqrt{\frac{q_c + q_r - q_s}{R(T_{avg})}} \quad (1)$$

Where q_c is the forced convection and is taken to be the higher of the values calculated for q_{c1} and q_{c2} as per the below Equation 2a and 2b, respectively.

$$q_{c1} = K_{angle} * \left[1.01 + 1.35 * N_{Re}^{0.52}\right] * k_f * (T_s - T_a) \quad (2a)$$

$$q_{c2} = K_{angle} * 0.754 * N_{Re}^{0.6} * k_f * (T_s - T_a) \quad (2b)$$

Where K_{angle} is calculated per Equation 3 and N_{Re} is calculated per Equation 4.

$$K_{angle} = 1.194 - \cos(\emptyset) + 0.194 * \cos(2\emptyset) + 0.368 * \sin(2\emptyset) \quad (3)$$

Where ϕ is the angle between the wind direction and the conductor axis.

$$N_{Re} = \frac{D_0 * \rho_f * V_w}{\mu_f} \quad (4)$$

Where:
D_0 is the outside diameter of the conductor
ρ_f is the density of air
V_w is the wind speed
μ_f is the absolute (dynamic) density of air.

Where q_r is the radiated heat loss rate and is calculated as per Equation 5.

$$q_r = 17.8 * D_o * \epsilon * \left[\left(\frac{T_s+273}{100}\right)^4 - \left(\frac{T_a+273}{100}\right)^4\right] \quad (5)$$

Where:
D_0 is the outside diameter of the conductor
T_s is the surface temperature of the conductor
T_a is the ambient temperature.

Where q_s is the rate of solar heat gain and is calculated from Equation 6.

$$q_s = \alpha * Q_{se} * \sin(\theta) * A' \quad (6)$$

Where:
α is the solar absorptivity
Q_{se} is the total solar and sky radiated heat intensity corrected for elevation
A' is the projected area of the conductor
θ is given by Equation 7.

$$\theta = arccos[\cos(H_c) * \cos\,(Z_c - Z_1] \quad (7)$$

Where:
H_c is the altitude of the sun (0 to 90)
Z_c is the azimuth of the sun
Z_1 is the azimuth of line.

Where $R(T_{avg})$ is the AC resistance of the conductor at average temperature and is calculated by Equation 8.

$$R(T_{avg}) = \left[\frac{R(T_{high}) - R(T_{low})}{T_{high} - T_{low}}\right] * (T_{avg} - T_{low}) + R(T_{low}) \quad (8)$$

Where:
T_{high} is the high average conductor temperature for which AC resistance is specified
T_{low} is the low average conductor temperature for which AC resistance is specified
T_{avg} is the average temperature

Line loss for each ACCC® and ACSR conductor was calculated from Equation 9.

$$P(loss) = \frac{P^2 R}{V^2} \quad (9)$$

Where:
P is the power of the line, calculated as the product of current and voltage. The current calculated for ACSR was used to calculated power for both conductors so that power would be comparable between the ACCC® and ACSR.
R is the resistance at peak operating amps
V is the voltage.

The line losses, given in MWh per year were converted to metric tons CO_2 using the appropriate emission factor for each region.

$$Emissions = line\ losses * emission\ factor \quad (10)$$